Enhancing actuation frequency of shape memory alloy-based system with a novel evaporative cooling technique for fast cyclic applications

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ABSTRACT

Recent advancements in the field of material science and robotics have resulted in smart, adaptive, and intelligent systems for in-field applications. Conventional electromagnetism-based actuators contribute significantly to the size and weight of these systems, and hence, they are not suitable for mobile robots. Shape memory alloys (SMA) have emerged as better alternatives due to their unique characteristics, such as high force-to-weight ratio, noiseless operation, and muscle-like motion, with the potential to develop novel actuation for biomedical, space, and robotic applications. SMAs regain their shape at higher temperatures through the shape memory effect. This effect causes the alloy to transform its shape and then fully recover during phase transition. SMA actuators have been thoroughly examined for their potential integration into robotic hands, arms, and manipulators. However, relatively long cooling times to retransform from austenite to martensite state make SMAs unsuitable for fast and rapid cyclic applications. The current research aims to examine the effect of an evaporative (spray) cooling technique using acetone, methanol, and deionized water as cooling agents on the cooling time of SMA. Comparative studies are performed to study the effect of different coolants on a 1-DOF SMA coil actuator. Furthermore, a SMA-based rotary actuator has been developed, demonstrating the feasibility of implementing an acetone-based spray cooling technique. A control circuit is designed to regulate the spraying process over the SMA coils. This novel evaporative technique offers a significant improvement (154%) in the actuation frequency of the SMA-based actuation system compared to free convection. The findings underscore the potential of evaporative cooling methods to enhance the performance of SMA-based actuators, with implications for fast cyclic applications such as robotic systems.

Keywords: Shape memory alloy, Rotary actuator, actuation frequency, Evaporative cooling, Spray technique, Liquid coolants, Additive manufacturing

1. INTRODUCTION

Shape memory alloys (SMAs) are highly efficient actuators with numerous applications, making them popular and in demand. However, their low actuation frequency, which limits their speed, presents a significant challenge. The actuation frequency is inversely proportional to the total cycle time, which is the sum of the heating and the cooling time. Reducing this time increases the frequency, this can be achieved by decreasing either the heating or cooling time. Traditionally, SMA actuators have been cooled using natural convection, where the voltage input is dropped to 0 V, and the actuator cools passively, or through forced convection,[1] which utilizes an external medium like fans for additional cooling. To further enhance the cooling technique and improve actuation speed, we investigate the use of external coolants sprayed over the SMA wires using atomizers to induce evaporative cooling and significantly faster cooling rates.[2]

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Several researchers have explored diverse approaches to address the challenge of slow cooling times in SMAs. Active cooling methods have been attempted, such as speed forced air convection, which utilizes a compressor to blow air at high speed through a tube, achieving faster cooling but at the expense of increased power consumption.[1,3] Heat sinks, employing contact with an aluminum rod enabling conduction, have also been explored, offering faster cooling but introducing complexity to the system design. Quenching involves the water to be injected on the wire surface using a syringe.[4,5] Though the method is highly effective in reducing cooling time, it utilizes water, which poses compatibility issues with electrical circuits and disrupts subsequent heating cycles due to residual moisture (wetting). Thermal gel proved ineffective in the case of SMA due to the inability of the SMA wire to overcome the viscosity of the applied gel and generate sufficient heat for achieving contraction.[6] Other attempts include thermo-electric tablets to cool the SMA wire.[7] The tablet is constantly powered to maintain a low-temperature face, which is kept in permanent contact with the SMA wire. A heat sink is deployed to dissipate the generated heat during the experiment cycle, leading to increased power consumption.[8] It was also observed that the wire was continually cooled by the thermoelectric tablet, even during the heating phase, without improving dynamic performance. The mobile heat sink method demonstrated promising outcomes, exhibiting smaller cycle times, faster actuation frequencies, and reduced power consumption compared to static heat sinks. Additionally, it featured a position control system integrated with a temperature sensor to prevent overheating. Despite these advantages, the system's complexity and bulkiness constrained its potential applications.[9]

Using SMA actuators within coolant-filled soft tubes can indeed lead to rapid cooling, but this comes with a trade-off of higher power input, as heat is dissipated to the coolant even during the heating phase.[5] Another approach akin to this is the Bowden tube method, primarily devised to transmit antagonistic forces from one location to another through a flexible package. The Bowden tube offers high flexibility, allowing easy integration of a long SMA wire without the need for a parallel wire configuration and pulleys. In this setup, a system was implemented to expedite the cooling of the SMA wire compared to exposure to open air, thereby enhancing position control.[10,11] The PTFE (Polytetrafluoroethylene) tube served as a heat sink to dissipate the heat generated during the experiment. However, a limitation of this setup was that while it achieved an increase in the speed of response of the SMA actuator, it did so at the expense of higher power consumption and increased mass.[12,13] Finally, a recent study aimed to enhance the actuation frequency of SMA wire by inducing vibration in the actuator during the cooling process, thereby increasing the convective heat transfer coefficient and facilitating faster cooling. In this experiment, an electromagnet was employed to induce vibration in the SMA wire actuator as it cooled.[14] The effectiveness of vibration-enhanced cooling was evaluated experimentally by observing the wire's actuation against a hanging weight and an extension spring. While this method proved highly efficient, it posed challenges for applications requiring the SMA wire to be routed around spools, pulleys, or any components that would impede vibration. Additionally, it was noted that the approach generated noise, making it unsuitable for applications where silence is crucial.

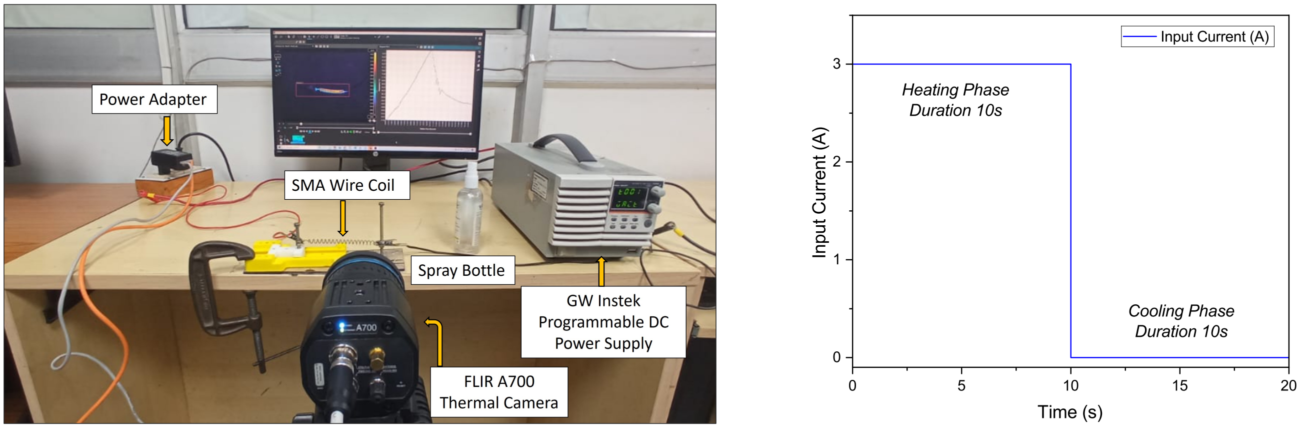
The current research explores the effect of evaporative (spray) cooling methods using liquid cooling agents like acetone, methanol, de-ionized water, and iso-propyl alcohol during the SMA cooling phase. A 1-DOF SMA coil slider system has been developed and actuated using Joule heating through an input pulse voltage. Experiments were conducted with a 3A input pulse current for 15 seconds, constituting the heating phase. During the cooling phase, the setup was subjected to 1) natural convection, 2) forced convection, and 3) external cooling agents. The results showed that the higher volatility of the compound played a crucial role in avoiding quenching effects that could alter the subsequent heating cycle. Acetone with 99% purity demonstrated the fastest evaporative cooling properties, leading to instant evaporation and minimal flooding. A full-fledged SMA-based rotary actuator was fabricated to compare cooling times. The cooling time for the SMA wire from 88°C to 32°C (ambient temperature) using free convection was 78 seconds, while acetone-based evaporative cooling achieved the same temperature reduction in only 21 seconds. This novel evaporative technique offers a significant improvement (154%) in the actuation frequency of the SMA-based actuation system compared to free convection. This research contributes to a deeper understanding of evaporative cooling methods in SMA-based actuation systems, paving the way for their application in fast cyclic applications such as robotic hands, arms, and manipulators.

2. METHODOLOGY

2.1 Comparative study of different cooling methods on 1-DOF SMA coil

The prototype incorporating a 1-DOF SMA coil is experimentally investigated to assess the performance of the different cooling techniques on a SMA-based linear actuator. The experimental setup, as shown in Figure 1a, consists of a programmable DC power supply to provide input current to the SMA wires. The temperature variation of the SMA wires is measured in real-time using a high-resolution science-grade LWIR camera (FLIR A700). A host computer records the data using ResearchIR software for further post-processing. When a current pulse of 3A is applied, the temperature of the SMA wire rises due to the Joule heating effect, causing the SMA wire to contract. For the cooling phase of the cycle, the setup was tested under six conditions for 10 seconds, as highlighted below. Figure 5 depicts the experimental result of time-dependent SMA wire temperature for a 3A input current pulse with different cooling techniques deployed.

1. **Natural convection:** Setting the input current to 0A and allowing the setup to cool down passively.
2. **Forced convection:** Employing a fan to enhance cooling during the cooling cycle.
3. **Liquid coolants:** Spraying the following coolants on the SMA coil during the cooling phase of the cycle.
   (a) Methanol 99.5%
   (b) Deionized water
   (c) Isopropyl alcohol 99.5%



(a) (b)

Figure 1: (a) The SMA-based linear actuation system was set up to measure the temperature drop in the SMA wire during the cooling phase. A 3A current pulse is supplied using a GW Instek programmable DC power source, and the results were recorded using a FLIR A700 thermal imaging camera. (b) The SMA coil is subjected for 10 s with a 3A input current (heating phase) and then allowed to cool for the next 10 s (cooling phase)

2.2 Investigating the effect of pure and mixture of liquid coolants on temperature profile

Figure 2 illustrates the experimental setup designed to investigate the impact of both pure and mixed liquid coolants on the temperature of the aluminum plate. This study aims to identify the most effective coolant for achieving the highest cooling rate of the aluminum plate. Utilizing a thermocouple wire, temperature measurements were conducted on an aluminum plate subjected to pure coolant and various coolant mixtures. To initiate the experiment, the aluminum plate was heated to approximately 93°C using a heating plate, after which the coolants were manually sprayed onto the plate using a sprayer. The timing of the sprays was adjusted in a manner to ensure that the subsequent spray occurred only after the complete evaporation of the previous one, thus preventing flooding—i.e., the accumulation of liquid on the plate's surface. Temperature readings were captured via a thermocouple connected to one end of the aluminum plate and a data logger on the other end. The recorded data was then plotted using PicoLog software for analysis.

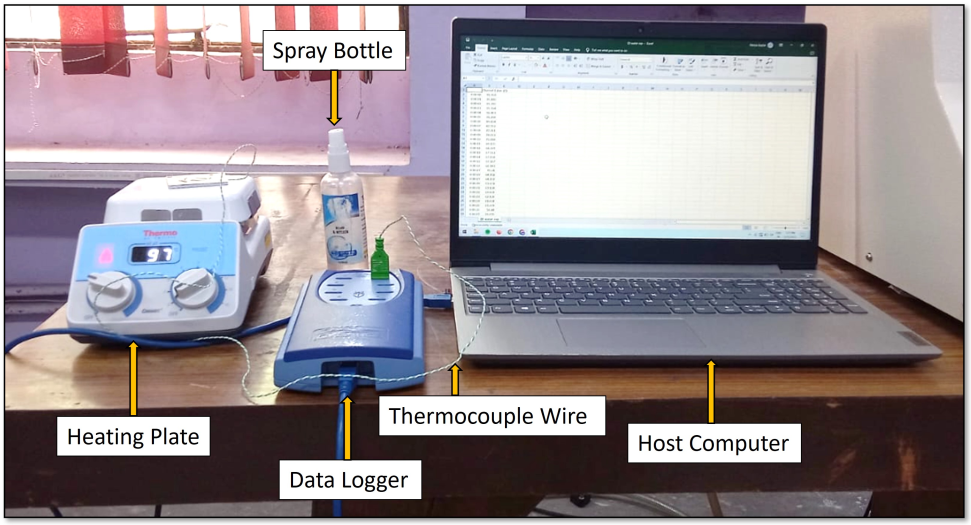


Figure 2: Experimental setup depicting the aluminum plate subjected to pure coolant and various coolant mixtures where temperature profile were measured using a thermocouple wire.

2.3 Concept and prototyping

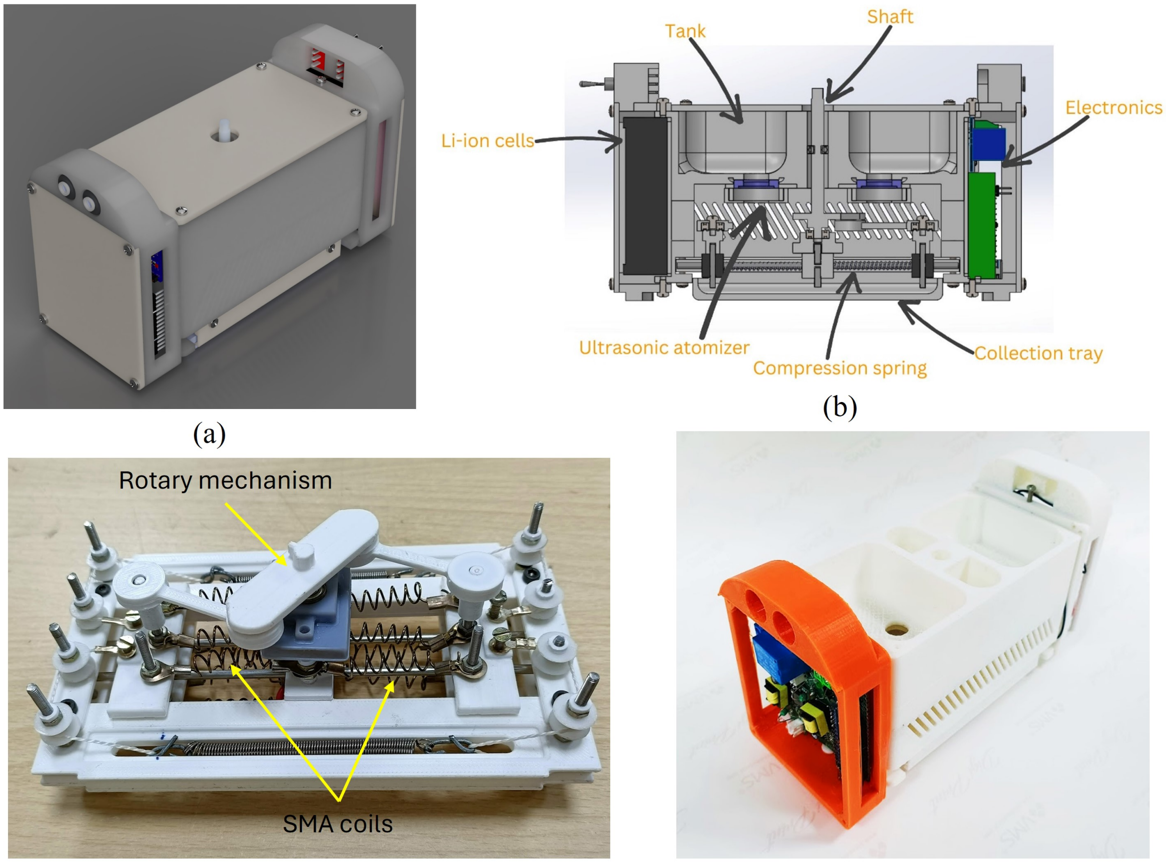
As a proof of concept, a SMA-based rotary actuator was developed to validate the performance of acetone-based cooling compared to free convection. The CAD model of the SMA-based rotary actuator is depicted in Figure 3a. In Figure 3b, a cut-section view of the actuator highlights a coolant storage tank positioned above the SMA coil chassis, utilizing gravitational potential to maintain a constant pressure head over the atomizers attached at the bottom face of the tank. The atomizers spray the acetone from the top directly on the SMA coils, and the excess is collected in the tray below. The configuration of components in the acetone-cooled actuator is illustrated in Figure 3b. On the other hand, Figure 3c and d represent chassis depicting novel rotary mechanisms and fully assembled SMA-based rotary actuation system, respectively. The actuator components were fabricated using additive manufacturing with the Ultimaker 3 Extended 3D printer, employing poly-lactic acid (PLA) as the primary material. Components in contact with acetone were coated with chemically resistant epoxy and silicone sealant to ensure a leak-proof arrangement around the atomizers. Furthermore, the shape memory alloy coils used for the experimentation are Flexinol actuator coils sourced from *Dynalloy, Inc.*

Figure 3c displays the assembled chassis housing with four SMA coils on the top and six on the bottom, connected in series and arranged symmetrically about the base frame. Each SMA coil is linked to the central body on one end and to the slider on the other, with compression springs positioned on the sliding shaft of the slider to act as bias springs. A slider-crank mechanism is devised to convert the linear actuation of the sliders into rotational actuation of the shaft.

S No.	Item	Technical specifications
1	Micro-controller	Arduino Nano
2	Current sensor	Current sensor module (ACS712, Range: 30A)
3	Relay	Single Channel 5V Relay Module
4	Battery	3.75 V Li ion cells
5	Voltage converter	Mini 360 Step-Down Buck Converter Power Module
6	Atomizer	USB Ultrasonic Humidifiers Power Circuit Board
7	Miscellaneous	Banana sockets, toggle switches

Table 1: Detailed description of the components incorporated into the controller circuit.

To regulate the atomizers, an electronic circuit was designed to spray acetone onto the SMA wires when the current to the SMA coils reaches zero. Table 1 shows the detailed description of the components incorporated



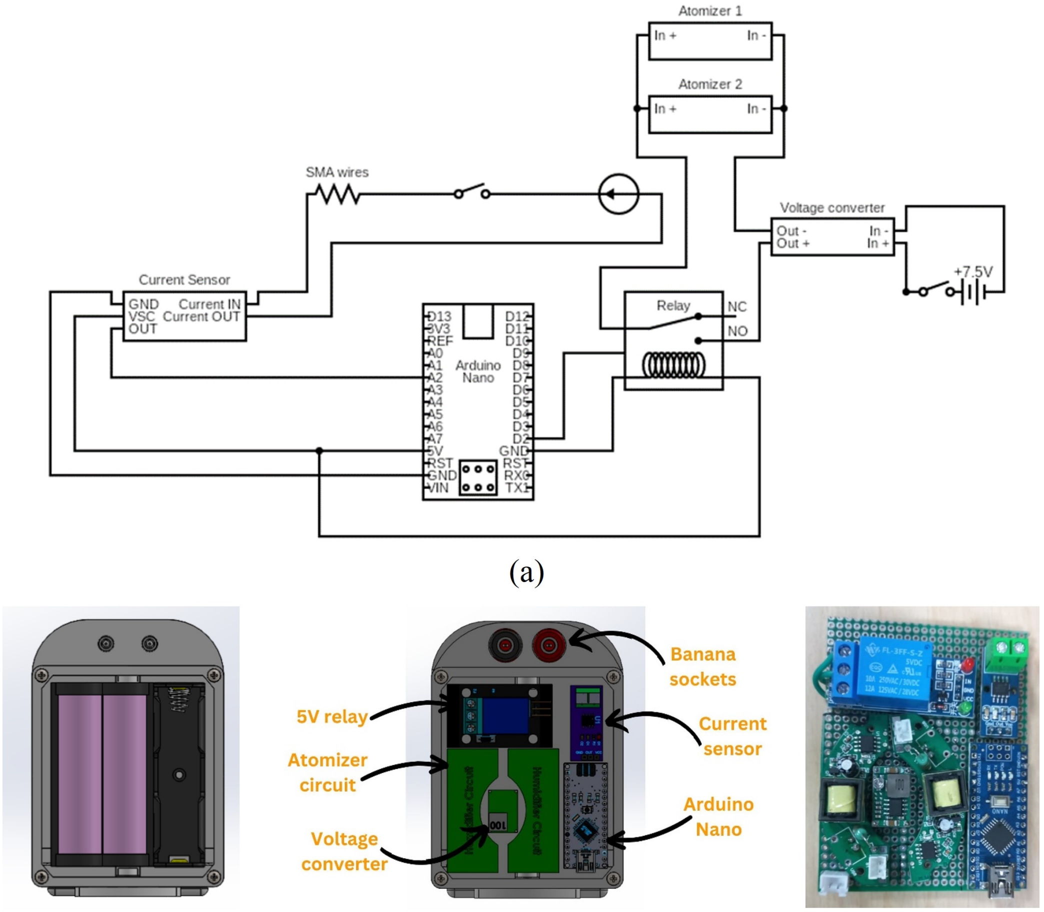
(a) (b) (c) (d)

Figure 3: Shape memory alloy-based rotary actuation system incorporating spray cooling mechanism. (a) depicts the CAD model of the system, (b) highlights different components in the cut-section view of the actuator, (c) showcases the chassis housing SMA coils and rotary link mechanism, (d) represents the fully assembled model.

into the controller circuit. Firstly, the Arduino Nano micro controller receives input from the current sensor, deployed to detect current in the SMA coil circuit. In the absence of detected current, the relay switches are activated to supply power to the atomizer. This protocol initiates spray cooling on the heated SMA coils, commencing the cooling phase. Figure 4a illustrates the electronic circuit diagram, detailing the connections among the various components. The Arduino Nano provides output to the 5V relay, governing the power supply from the two Li-ion cells to the two atomizer circuits. One of the toggle switches controls the power supply from the programmable DC power supply to the SMA wires, turning them ON or OFF. Figure 4b showcases the arrangement of electronic components in both the CAD model and the actual printed circuit board (PCB). Components were strategically positioned on the PCB board sideways to safeguard them from exposure to the coolant spray.

3. RESULTS AND DISCUSSION

Figure 5 depicts the variation of SMA coil temperature over the total cycle time when subjected to an input pulse duration of 10s followed by a cooling phase of 10s, as specified in Figure 1b. The plot provides a comparative analysis of three cooling techniques: free convection, forced convection, and cooling via liquid coolants applied at uniform intervals. This comparison underscores the significant temperature reduction achieved through the use of liquid coolants and forced convection, rendering free convection comparatively less effective. Data acquisition was performed utilizing the FLIR thermal camera, and subsequent analysis was conducted using the FLIR Research Studio software. The plot highlights that among forced convection and other liquid coolants, such as isopropyl



(a)

(b)

Figure 4: (a) illustrates the electronic circuit diagram, detailing the connections among the various components, and (b) depicts the CAD model and the corresponding actual printed circuit board.

alcohol and 99% methanol, the most substantial temperature drop is observed with deionized water. This can be attributed to two primary processes. Firstly, sensible heat transfer is responsible for maintaining thermodynamic equilibrium between the SMA wire and the water adhering to it after spraying. Secondly, evaporative (spray) cooling occurs, wherein the heat transferred during the conversion of the liquid sprayed onto the wire into vapor contributes to cooling.

While forced convection induces a significant temperature reduction in the SMA coil, it is not favored due to its higher power consumption and comparatively less effective cooling compared to liquid coolants. Conversely, with other coolants, sensible heat transfer is absent, and only evaporative cooling contributes to the temperature drop. However, a drawback of using water is its unsuitability and lack of preference as a coolant in electronic circuits. Additionally, it can lead to flooding or quenching effects, where the liquid persists on the wire after spraying, disrupting subsequent heating cycles.

Figure 6 illustrates the comparison between the effects of five different pure and coolant mixtures—acetone 99%, methanol 99.5%, de-ionized water, acetone 99%: de-ionized water (50:50), and methanol 99.5%: de-ionized water (50:50)—on the temperature drop of an aluminum plate. The data recorded using the PicoLog data logger reveals that de-ionized water and its mixtures linger on the surface of the aluminum plate for some time before evaporating completely, causing flooding. This disturbance during the heating phase of the subsequent cycle impacts the highest temperature reached by the wire. While methanol 99.5%, being more volatile than

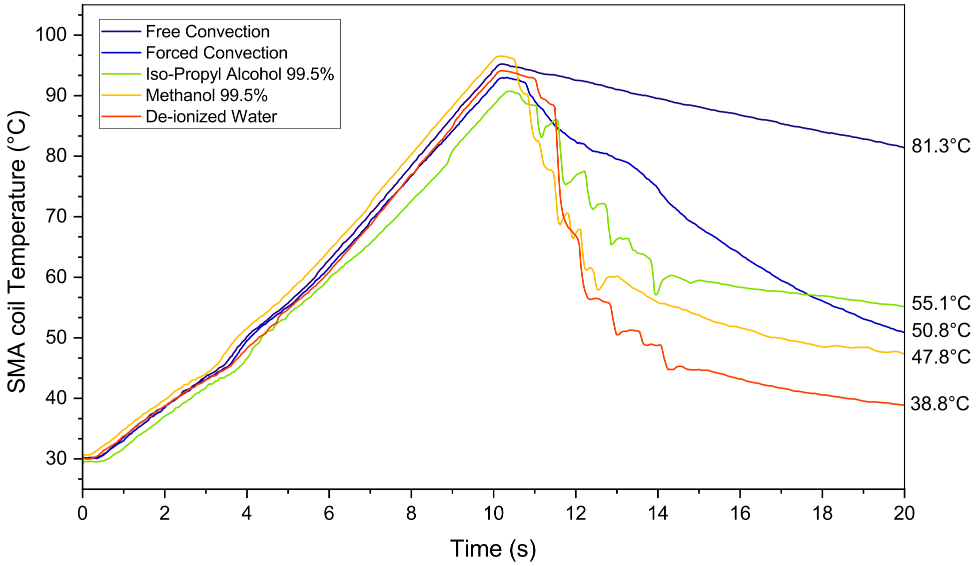


Figure 5: Comparison between the effect of free convection, forced convection, and liquid coolants on the temperature of SMA coil during the cooling phase, under a cycle with an input pulse of 3A for 10s followed by a cooling phase for 10s

de-ionized water, induces a significant cooling effect, the most substantial temperature drop is observed in the case of acetone 99% as it is highly volatile and leads to fast evaporative cooling, resulting in instant evaporation, profound cooling effect, and almost negligible flooding conditions.

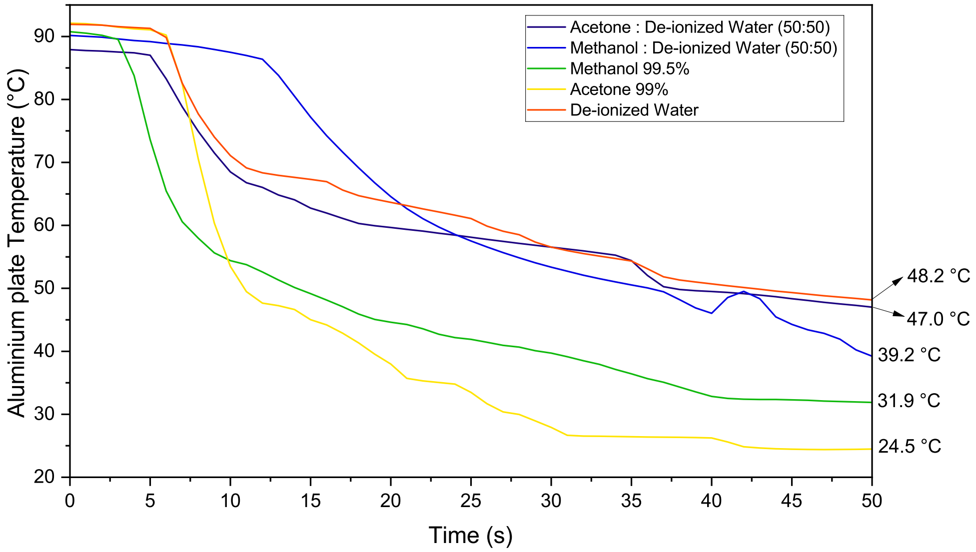


Figure 6: Comparison between the effect of pure and mixture of coolants on the temperature of aluminum plate during the cooling phase, under a cycle with an input pulse of 3A for 10s followed by a cooling phase for 10s.

Figure 7 highlights the variation of SMA coil temperature under different cooling agents across two complete cycles of input current pulses. During each cycle, the SMA coil is subjected to a 3A input current for 10 seconds (heating phase) followed by a 10-second cooling phase, highlighting the persistence of residual heat in the coil and its impact on subsequent cycles. The plot clearly depicts that with methanol 99.5% and acetone 99%, the coil temperature drops to ambient levels by the end of the cooling phase. Conversely, free convection exhibits a significant amount of residual heat, which, during subsequent cycles, can cause the coil to reach its self-actuating temperature without external heating, thereby adversely affecting the shape memory effect. Although both methanol 99.5% and acetone 99% result in an equivalent temperature drop in the coil, acetone 99% is preferred over methanol 99.5% due to its high volatility. This property allows acetone to evaporate instantly, preventing flooding and ensuring it does not persist on the surface of the SMA wire, thereby maintaining the integrity of the second heating phase of the cycle.

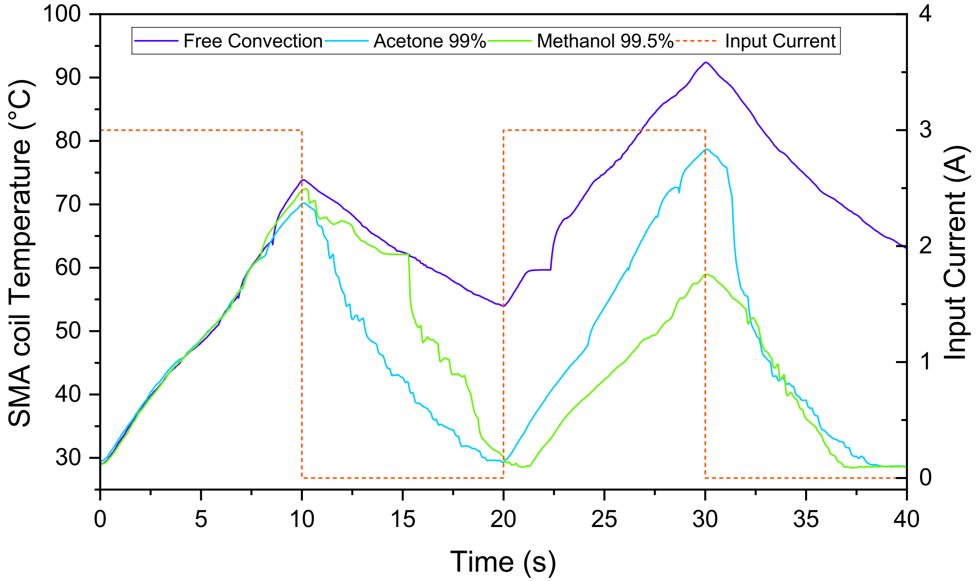
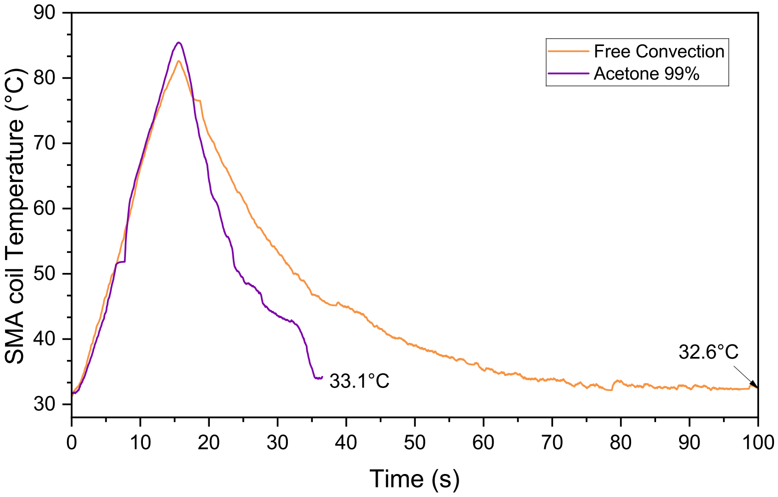


Figure 7: Comparison of the effect of Free convection, Methanol 99.5%, and Acetone 99% on the variation of SMA coil temperature under 2 cycles with an input pulse of 3A for 10s followed by a cooling phase for 10s



(a)

Cooling method	Free Convection	Acetone 99%
Heating time (t_H)	15 s	15 s
Coolig time (t_C)	78 s	21 s
Total time ($t_H + t_C$)	93 s	36 s
Frequency (f)	11 mHz	28 mHz

(b)

Figure 8: (a) Time taken by the SMA coil to reach the ambient temperature under the effect of free convection and Acetone 99% evaporative cooling when supplied with 3A of current for 15s followed by the cooling phase (b) Comparison of actuation frequency for free convection and acetone-based evaporative cooling

Figure 8 presents a comparative analysis between Acetone 99% based cooling and free convection, conducted on a SMA-based rotary actuator. The cycle comprises an input pulse of 3A for 15s, succeeded by a cooling phase that persists until the SMA coil reaches ambient temperature. The plot illustrates the variation of SMA coil temperature over the total cycle time. The slope preceding the peak temperature signifies the heating phase, while the subsequent segment represents the cooling phase. It is evident from the plot that the cooling time for the SMA coil to reach ambient temperature is 21s with acetone cooling, corresponding to a frequency of 28 mHz. In contrast, during free convection, the SMA coil takes 78s to cool down, resulting in a frequency of 11 mHz. This indicates that Acetone 99% based cooling enhances the actuation frequency of the SMA-based muscle actuator by 2.54 times.

4. CONCLUSION

This paper explores and presents a novel cooling method to enhance the actuation frequency of SMA actuators. Despite possessing several advantages, including a high power-to-weight ratio, noiseless operation, and adaptability to miniaturization, the low actuation frequency of shape memory alloy actuators limits their applications. To address this challenge, the current research conducted a series of experiments aimed at minimizing the cooling time of SMAs, thereby improving their actuation frequency. A comparative study was conducted on a 1-DOF SMA coil using different cooling methods, including free convection, forced convection, and various liquid coolants (methanol 99.5%, deionized water, and isopropyl alcohol 99.5%). Additionally, experimental investigations were carried out to understand the effect of pure and mixed liquid coolants on the temperature profile of an aluminum plate. The outcomes of the study highlight that the spray cooling technique with acetone as a liquid coolant could be a better alternative to existing cooling methods used for SMA cooling. A techno-feasibility study was conducted to integrate the spray cooling technique with a working model of an SMA-based rotary actuation system. This novel evaporative technique demonstrates a significant improvement (154%) in the actuation frequency of SMA-based actuation systems compared to free convection. Overall, this research contributes to a deeper understanding of evaporative cooling methods in SMA-based actuation systems, thereby paving the way for their application in fast cyclic applications such as robotic hands, arms, and manipulators.

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